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Understanding Sediment Sources, Pathways and Sinks in Regional Sediment Management: Wash Load and Bed-Material Load Concept

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PURPOSE: As water resource projects become more and more complex, there is a growing emphasis on the ability to implement effective regional sediment management. A common goal of many regional sediment management (RSM) projects is the reduction of sediment loading from the watershed. This is usually accomplished by rehabilitation features such as grade control, bank stabilization, drop pipes, and land treatments. While these features are often implemented with the stated purpose of reducing sediment yields to downstream reservoirs, flood-control channels, or wetlands, the spatial and temporal impacts of these features with respect to downstream sediment loads are far from straightforward, and often result in unanticipated morphologic adjustments and degradation of riverine habitats and ecosystems. Effective regional sediment management lies in identifying the sediment sources and sediment sinks in the watershed sediment system and understanding the processes responsible for transferring sediment along the pathways that link sediment sources and sinks at the reach and catchment scales. This technical note describes how the concepts of wash load and bed-material load can be used to document the transfer of sediment from its source, through its pathways, to its ultimate sinks, thereby, serving as the foundation for effective regional sediment management.

INTRODUCTION: Requirements for new water resource and river management projects to meet objectives in ways that are environmentally and economically sustainable have led to increasing attention on associated impacts on sediment dynamics and sedimentation in the fluvial system. This is the case because engineering works and management actions that fail to account for sediment dynamics risk disrupting sediment transfer in the fluvial system, triggering new patterns of erosion and sedimentation that require increased maintenance or further engineering interventions, and with adverse environmental consequences. Sediment impacts are seldom confined to the project reach and may extend throughout the river network, which dictates the use of catchmentwide approaches that can underpin effective regional sediment management. While sediment impacts are increasingly taken into account at the design stage of new projects, many rivers bear the legacy of past schemes that inadvertently disrupted sediment dynamics. Often these disruptions are to the detriment of riverine habitats and ecosystems or higher than expected life-cycle costs due to maintenance necessary to preserve the effectiveness of flood defense, navigation, or land drainage functions. Hence, the goal of many RSM initiatives is to reduce elevated sediment loadings in previously disturbed river networks and restore connectivity in dysfunctional sediment transfer systems.

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Regional sediment management is usually accomplished through channel rehabilitation that employs features such as grade control structures to control the longitudinal profile of the stream, bank stabilization to reduce sediment inputs, drop pipes to stabilize stream-side gullies, and soil conservation measures to reduce catchment sediment yield (Hudson 1997). However, while the primary purpose of a project may be to return the rate of sediment delivery to a reservoir, flood-control channel, or wetland to some predisturbance level, it is still necessary to analyze the sediment impacts within a whole-catchment context. This is essential because of complexity in the spatial and temporal dimensions of catchment sediment processes and morphological responses. In many rivers and streams, management of downstream sediment loads is far from straightforward. The risk exists that a scheme designed without consideration of catchmentwide sediment dynamics will solve one sediment related problem at the expense of creating new sediment imbalances and unintended morphological responses elsewhere in the fluvial system.

The key to optimizing management of sediment dynamics in the fluvial system lies in identifying the sediment sources and sediment sinks and understanding the processes responsible for transferring sediment along the pathways that link sediment sources and sinks at the reach and catchment scales. While a great deal has been written about sediment transport, there is much less in the literature concerning sediment transfer, and there is surprisingly little published guidance on how sediment sources, pathways, and sinks can be identified and characterized within the context of project-related studies. Although detailed knowledge of the processes and mechanics of sediment transport informs sediment transfer studies, the complexity and large scale of catchmentwide sediment dynamics preclude analysis using an approach that starts with the movement of individual grains. What is needed is a broader consideration of the sediment transfer system that supports higher-level treatment by reproducing the main functions and responses without attempting detailed replication of sediment transport processes. This technical note describes how the concept of wash load and bed-material load can be used to quantify the transfer of sediment from its source, through its pathways, and to its ultimate sinks thereby providing a reliable analytical foundation for effective regional sediment management.

SEDIMENT DEFINITIONS: Historically, sediment moving in a stream has been defined on the basis of the method by which it is measured, the mechanism by which it moves, or the source from which it is derived (Simons and Sentürk 1977). The distinctions between these classifications are not always obvious and are shown comparatively in the tabulation. The size of the boxes in the tabulation are not intended to show absolute amounts of the various loads, rather they illustrate that the various loads are not necessarily equal.

Alternative Approaches to Sediment Transport Classification

Measurement Method	Transport Mechanism	Sediment Source
Measured Load	Suspended Load	Wash Load
Unmeasured Load	Bed Load	Bed-material Load

Typically in the United States, sediment load data are collected at gauging stations based on measurements using a cable-suspended, nozzle sampler that is lowered and raised through the water column by winch. This technique samples most of the suspended load, but the sampled zone does not extend all the way to the streambed and, consequently, the near-bed portion of the suspended load and the entire bed load are not sampled and remain unmeasured. Although the unmeasured load cannot be established by conventional sampling, it may subsequently be estimated based on the flow hydraulics and measured load using the Einstein-Brown sediment transport formula (Brown 1950). Alternatively, the unmeasured load may be sampled using a specially designed device such as a Helley-Smith sampler, which is often thought of as a bed-load sampler, although the original purpose was to sample the unmeasured load at U.S. Geological Survey (USGS) gauging stations (Helley and Smith 1971). The total sediment load at the station is made up of the measured load plus the unmeasured load.

Sediment in motion can also be classified as either bed load or suspended load, according to its transport mechanism. Bed load is made up of particles that are rolling, sliding or saltating and which are, therefore, in either continuous or intermittent contact with the bed. Suspended sediment moves in the water column above the bed and is rarely in contact with the bed. The distinction between bed and suspended loads is not obvious in the field, but it is physically significant and can be made on theoretical grounds. Bagnold (1966) demonstrated that the submerged weight of grains moving as bed load is supported solely by solid-to-solid contact at the bed, while that of suspended load is supported entirely by anisotropic turbulence due to fluid shear flow. The total load is the sum of the bed load and suspended load. Generally the sampler used to measure sediment in transport collects the majority of the suspended sediment while leaving a portion of the suspended sediment close to the bed and the sediment moving as bed load unmeasured.

The third basis for classification of the sediment load is by the source of the sediment within the catchment. The bed-material load is the sediment in transport that comprises particles found in appreciable quantities in the channel bed. Wash load is sediment in transport that is derived from sources other than the bed. It is finer than the bed-material load and is not found in appreciable quantities in the bed, e.g. banks, gullies, and runoff. The total load consists of the sum of the bed-material load and the wash load. With respect to channel morphology, the bed-material load is the more important component of the total load because it is derived from erosion of the channel bed, because bed-material load particles are constantly being exchanged with particles in the bed, and because it returns to the bed at the end of a transport event.

DEFINING WASH LOAD: The distinction between bed-material load and wash load components of the total load adopted here is that wash load is not found "in appreciable quantities" in the bed of the channel. However, the precise definition of what constitutes an "appreciable quantity" is unclear, meaning that the threshold grain size separating bed-material load and wash load may be defined in several ways. Einstein (1950) defines wash load as the grain size of which 10 percent of the bed mixture is finer. "This basically different behavior of the fine and the coarse particles in the same channel has led the author and collaborators to assume that the fine particles in the flow still behave like material called "wash load" in the concrete channel, whereas the coarse particles act like the sediment in a strictly alluvial channel. These investigators give the limiting grain size between wash load and alluvial or bed load in

terms of the composition of the sediment deposit in the bed. They state that all particle sizes that are not significantly represented in the deposit must be considered as wash load. More specifically, the limiting size may be arbitrarily chosen from the mechanical analysis of the deposit as that grain size of which 10 percent of the bed mixture is finer. This rule seems to be rather generally applicable as long as low-water and dead-water deposits are excluded from the bed sediment." There is no theoretical justification for selecting D_{10} rather than some other percentile at the lower end of the bed-material size gradation curve (the D_5, or D_{15}, might equally well be proposed), but the principle accepted here is that wash load may be defined on the basis of its absence from the bed material and that any size criterion used to define it must, therefore, be expressed in relative rather than absolute terms. It follows that while silt and clay would be defined as wash load in a sand-bed channel, the wash load in a gravel-bed channel would include the sand fraction of the sediment load provided that the D_{10} of the bed was 2 mm or coarser.

It should be noted that the definition of wash load adopted here is by no means universally applied or accepted. For example, wash load has also been defined as consisting of particles smaller than 0.063 mm, corresponding to the division between sand and silt in the Wentworth scale (Yang and Simões 2005; Knighton 1998; Richards 1982). Bettess (1994) defines the wash load as: "… sediment that moves in suspension in the flow but is not represented in the bed of the channel. It is generally assumed that the transport of the wash load is supply dependent and is independent of the local flow conditions." Graf (1984) agrees with Einstein, pointing out that the wash load is made up of sizes finer than the bulk of the bed-material load, and states: "The wash load rate can be related to the available supply of solid particles within the watershed; it enters the watercourse by sheet wash, bank caving, etc., but is merely washed through the sections." However, none of these definitions has the breadth of applicability of the definition adopted here. For example, as previously noted, in gravel-bed rivers, sand may not be found in appreciable quantities in the bed and so it should be considered wash load as the source must lie away from the bed. Also, in laterally active channels, much of the wash load may be derived from erosion of the channel banks, rendering inappropriate a definition restricted to input from slopes outside the channel.

WASH LOAD AND BED-MATERIAL LOAD CONCEPT: There is no universally accepted definition of wash load, yet despite this, the wider concept that sediment in transport that is finer than that making up the bed of the channel behaves differently and plays a different role in the sediment transfer system is widely perceived to have merit and has often proven useful in river-engineering studies (Einstein 1950). In this respect, there are three tenants within the wash load and bed-material load concept that are relevant from a practical regional sediment management perspective.

First, because wash load is fine relative to the bed-material load, the stream does not need to expend significant amounts of energy in transporting it through the fluvial system. It follows that changes in the quantity of wash load in transport (due to the addition or removal of wash load sources) will seldom trigger significant morphological responses and marked changes to the stability of the channel. Conversely, imbalances in the bed-material load will usually drive local morphological response through channel scour (where transport capacity exceeds supply) or fill (where supply exceeds transport capacity).

Second, the quantity of wash load carried by a stream is limited not by the stream's sediment transport capacity, but by the available supply. It follows that it is only the bed-material load that most sediment transport equations can calculate on the basis of the transport capacity indicated by the local flow hydraulics. Wash load transport cannot be predicted this way, but can only be estimated on the basis of comprehensive, quantitative assessment of wash load sediment sources.

Third, the movement of wash load is relatively rapid compared to that of the bed-material load. In a sand-bed channel, where the wash load is composed of fine sands, silts and clays that are fairly evenly distributed throughout the water column, wash load may move through the channel system at a speed approximating the mean flow velocity. It follows that fines moving as wash load may travel from upstream sources to downstream sinks during single transport events, so that variations in wash load supply are quickly reflected in rates of downstream siltation. Conversely, in cobble and boulder-bed channels, the movement of gravel-sized wash load moving as bed load is much slower, resulting in longer travel times for coarse wash load moving from headwater sources to downstream sinks. Consequently, in coarse-bed systems, response times for the impacts of changes in wash load sources to be realized might be measured in decades rather than the months or years evidenced in sand-bed rivers.

It must also be recognized that spatial variation in the wash load and bed-material load threshold, grain size is inherent to most fluvial systems. Generally, the upper bound grain size for the wash load becomes finer in the downstream direction due to downstream fining of the bed material. Typical examples of this trend are shown in Figures 1 and 2, for D_{10} values from the Missouri and Mississippi Rivers, respectively. On the Missouri River, the bed material D_{10} value immediately downstream of the Garrison Dam is 0.2 to 0.25 mm, but decreases to less than 0.1 mm as the river encounters the backwater effects of Lake Oahe (Figure 1). In this case, fining of the wash load may be attributed largely to the pool effects of the lake, however, a similar trend can be found in an open river situation along the Lower Mississippi River. For example, D_{10} values along the Mississippi River decrease from about 0.25 mm in the New Madrid, MO, to Memphis, TN, reach to about 0.063 mm below Baton Rouge, LA (Figure 2).

Spatial changes in the upper limit of wash load size such as these have important implications for sediment dynamics in the fluvial system. For example, where the threshold size decreases in the downstream direction, as in the cases presented earlier, then the coarser fraction of wash load entering a reach from upstream must be reclassified as bed-material load in that reach. As a result, the behavior of this fraction of the total load switches from that characteristic of wash load to that of bed-material load, with consequential impacts on local sediment dynamics and morphological responses.

Temporal changes in the wash load threshold grain size may also occur, but are more difficult to generalize. For example, the particle size distribution of the bed in some streams varies seasonally. In such cases, care would have to be taken to match the sampling strategy used to establish the D_{10} for the bed to the purpose of the study. For instance, it might be necessary to investigate seasonal variability in sediment impacts or to characterize long-term sediment dynamics that are independent of seasonal fluctuations.

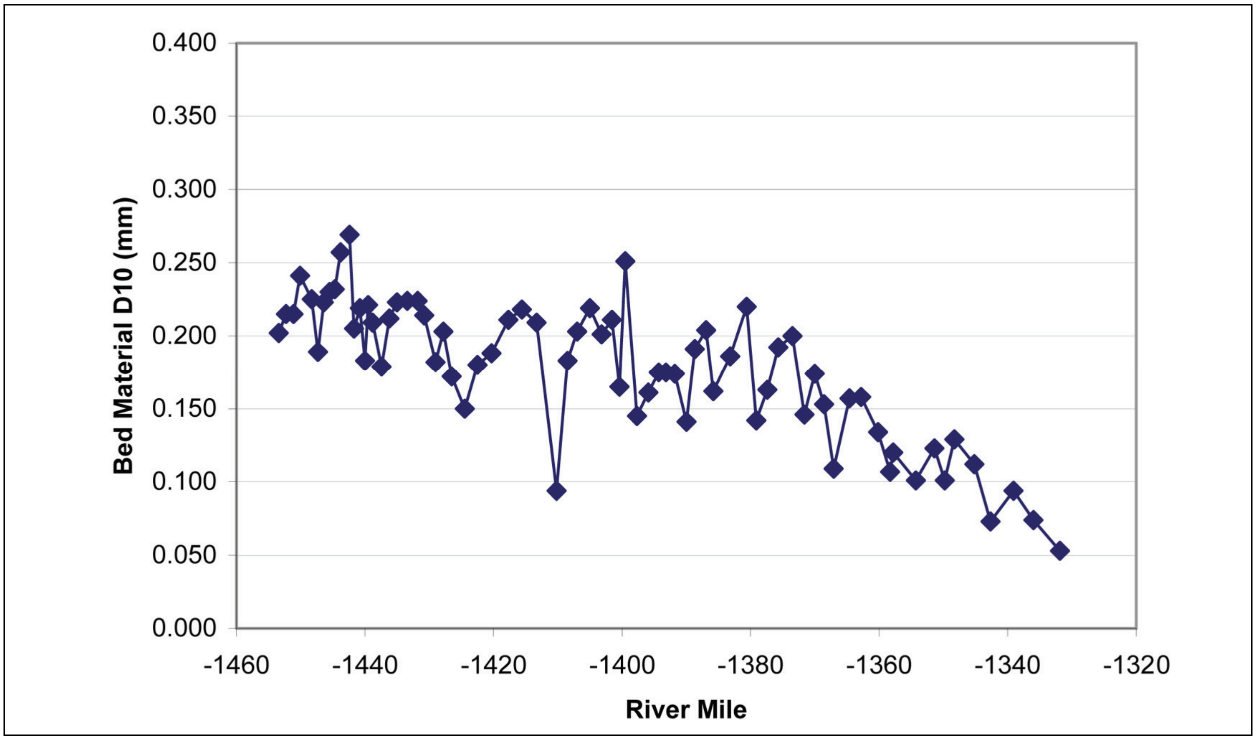

Figure 1. Bed material D_{10} values on Missouri River below Garrison Dam

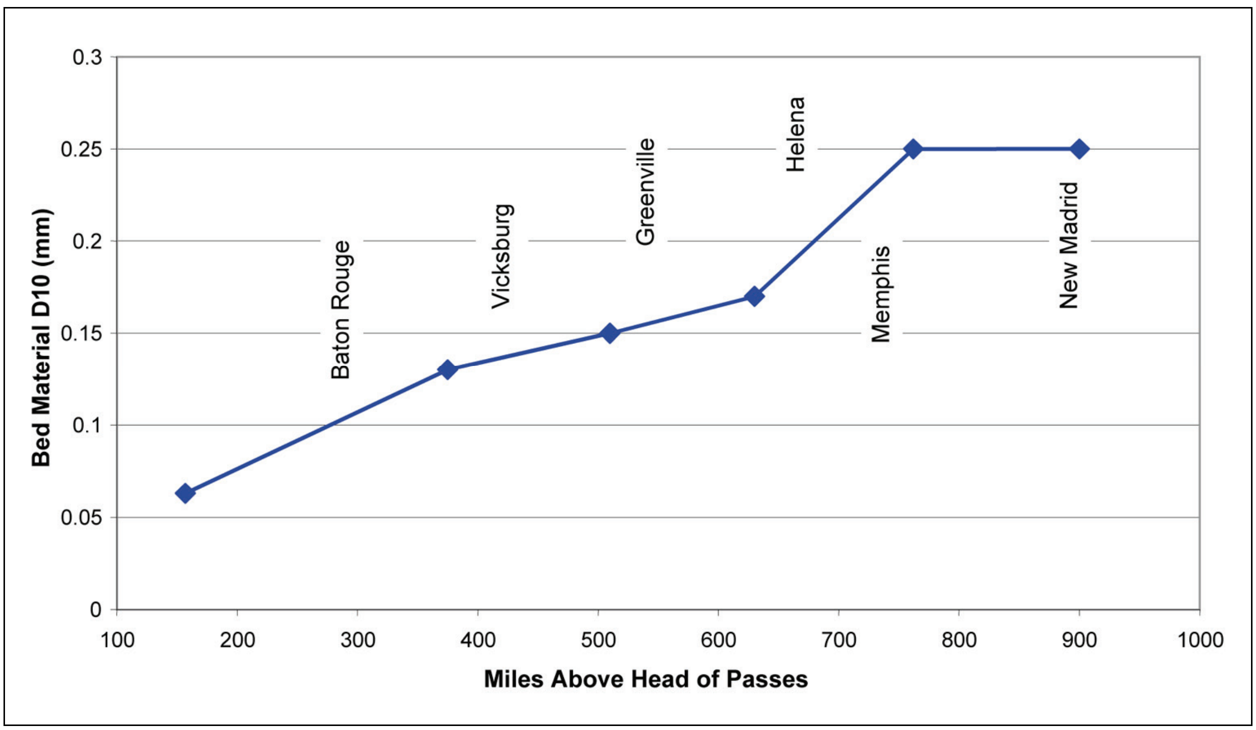

Figure 2. Bed material D_{10} along Lower Mississippi River (adapted from Nordin and Queen 1989)

APPLICATION TO REGIONAL SEDIMENT MANAGEMENT: While these abstract arguments concerning the behavior of sediment load classed according to the wash load and bed-material load concept illustrate the general utility of the concept, application to regional sediment management can better be illustrated using an example based on the D_{10} plot in Figure 2. For this example, consider a sediment source from a streambank erosion site at river mile 750 near Memphis, TN, where the bank is composed of material finer than 0.25 mm. Since the wash load – bed-material load threshold in this reach is about 0.25 mm, all of the material eroded from the bank will be supplied to the river at this location as wash load. Consequently, stabilization of this bank would have a minimal morphological impact in this reach because the source material is all wash load within the reach, and not contributing significantly to the morphology of the reach. However, downstream near Vicksburg, MS (river mile 435) where the bed-material-wash load threshold has decreased to about 0.14 mm, the channel would realize a reduction in the supply of bed material in the range of 0.25 mm to 0.14 mm. Thus, the Vicksburg reach would realize an almost immediate reduction in bed-material supply, and some sort of morphologic response would be expected. For instance, if the Vicksburg reach was experiencing aggradation, then the reduction in the bed material supply might lessen the aggradational trend. However, if the Vicksburg reach was in dynamic equilibrium, then the reduction in bed-material supply could potentially shift the channel to degradation. Now consider what would happen if the bank material source near Memphis was composed completely of material greater than 0.25 mm. In this instance, stabilization of the bank could have a more significant morphologic impact in the Memphis reach since a bed-material source has been removed. However, the short-term impacts to the downstream reaches would be minimal. In fact, there could be a considerable time lag before the downstream reaches experience any sediment reduction because these reductions would be purely a function of the morphologic adjustments in the Memphis reach. Obviously, these are hypothetical examples, and the actual response would depend upon the relative magnitude of the reduction in sediment supply and the morphologic characteristics of the river. These hypothetical examples do, however, illustrate how the concept could be used to assess the potential impacts of sediment management activities.

SUMMARY: The sediment impact analysis methodology presented here provides a conceptual basis for developing, designing, and optimizing erosion control and channel-improvement plans. In practice, predicting the magnitude of sediment impacts and the nature of morphological responses to the changes in flow and sediment inputs would require development of a quantitative sediment budget for the channel system that includes and accounts for all the significant sediment sources in the watershed. To this end, the Sediment Impact Assessment Model (SIAM) was developed. SIAM incorporates the wash load and bed-material load concept discussed herein, and enables rapid assessment of the impacts of changes in flow and sediment input throughout the channel system. The incorporation of SIAM into HEC-RAS will be available for beta application in September 2006.

ADDITIONAL INFORMATION: This technical note was prepared by David S. Biedenharn, research hydraulic engineer, Lisa C. Hubbard, research physical scientist, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Colin R. Thorne, professor, University of Nottingham, School of Geography, Nottingham, England, and Chester C. Watson, professor, Colorado State University, Department of Civil Engineering, Fort Collins, CO. The study was conducted as an activity of the Improved Characterization and Estimates of Sediment

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